

# **THE INTERNATIONAL GPS SERVICE (IGS) AS A CONTINUOUS REFERENCE SYSTEM FOR PRECISE GPS POSITIONING**

**Ruth Neilan<sup>1</sup>, Michael Heflin<sup>2</sup>, Michael Watkins<sup>2</sup>, James Zumberge<sup>1,2</sup>  
IGS Central Bureau &  
Satellite Geodesy and Geodynamics System Group  
Jet Propulsion Laboratory, California Institute of Technology  
4800 Oak Grove Drive Pasadena CA 91109**

## **ABSTRACT**

The International GPS Service for Geodynamics (IGS) is an organization which operates under the auspices of the International Association of Geodesy (IAG) and has been operational since January 1994. The primary objective of the IGS is to provide precise GPS data and data products to support geodetic and geophysical research activities. The IGS also provides support for diverse operational activities undertaken by government or commercial organizations. This paper will describe the IGS and relate this international effort to the U.S. nationwide program of the Continuously Operating Reference Stations (CORS).

## **HISTORY AND DEVELOPMENT OF THE IGS**

The international GPS Service for Geodynamics (IGS) has completed two fully operational years as an approved Service of the international Association of Geodesy (IAG). The IGS has two objectives: one is to provide support for geodetic and geophysical research activities which are dependent on GPS as a key technique. The IGS is also keeping pace with the rapid growth in GPS applications and, as a second objective, provides the support for a broad spectrum of operational activities performed by governmental and selected commercial organizations.

### GPS Global Network Development

The Coordinated international GPS Network (CIGNET) was an important early activity for global GPS reference control, and was coordinated by the U.S. National Geodetic Survey. \* The CIGNET network of 1989 was soon augmented by other international partners (Mader, Strange and Hothorn, 1989), and efforts focusing on implementing a standard, precision P-code tracking network helped to form the core of the initial IGS Network (Neilan, Melbourne and Mader, 1990).

Coordinated international network operations for the timely availability of quality data was essential. It became increasingly apparent that a pivotal point in establishment of a global reference network was the standardization of the infrastructure, and that the network should be continuously available, and reliable. This was the consensus of the international geodetic community and led to the planning of the IGS, beginning in 1989 to its official establishment in January 1994. A detailed history and development of the IGS is documented in the 1994 Annual Report of the IGS, available through the Central Bureau (Beutler, 1995).

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\* This was done within the GPS Subcommittee of the International Association of Geodesy's Commission VIII, the international Coordination of Space Techniques for Geodesy and Geodynamics (CSTG).

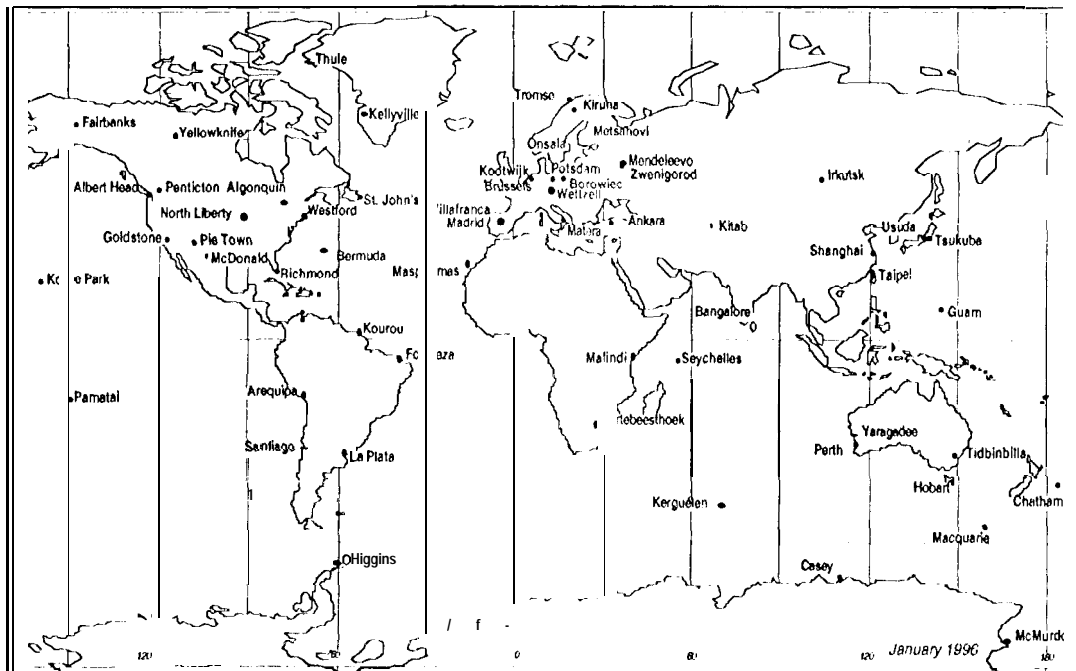


Figure 1. GPS Tracking Network of the International GPS Service for Geodynamics, January 1996., depicting the Global Stations, those stations that are analyzed by three or more IGS Analysis Centers. Regional GPS stations, as well as future planned stations can be identified by accessing the IGS Central Bureau information System.

#### IGS objectives and Organization

The IGS collects, archives and distributes GPS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experiments. These data sets are used by the IGS to generate data and products that are readily available and accessible to all users. These include high accuracy GPS orbits ( $\sim 10$  cm), earth rotation parameters, the coordinates and velocities of the ground tracking stations, GPS satellite clock information, and ionospheric information.

The generation of the data and products is accomplished through a global network of about 115 precise tracking stations, data centers, analysis centers, a Central Bureau and an International Governing Board. The IGS Central Bureau, located at the Jet Propulsion Laboratory and funded by the National Aeronautics and Space Administration, maintains an extensive data information system, which is accessible through anonymous ftp ([igscb.jpl.nasa.gov](http://igscb.jpl.nasa.gov)), and the World Wide Web (<http://igscb.jpl.nasa.gov/>).

### **OVERVIEW OF CORS**

The Continuously operating Reference Station (CORS) network is a set of GPS reference stations within the U.S., at this time primarily implemented by the U.S. Coast Guard and the U.S. Army Corps of Engineers. The Coast Guard is implementing these stations as a Differential GPS (DGPS) Network to establish a system that will meet the highly accurate navigation requirements for commercial and private mariners along the US Coast and within harbor areas (National Research Council, 1995).

The utilization of the DGPS stations for higher accuracy requirements has evolved into the CORS program. The CORS concept has been promoted and coordinated by the National Geodetic Survey, National Oceanic and Atmospheric Administration (NOAA), as a program to ensure the implementation of a consistent set of federally funded reference stations (U.S. Department of Commerce, 1994). A stated objective is that federally funded GPS stations, regardless of implementing agency, will meet the CORS specifications and be CORS compatible. This is also to include the Wide Area Augmentation Systems (WAAS) being planned by the Federal Aviation Administration (FAA). By agreement, NGS will utilize these stations and will make the data available. CORS is intended to provide GPS data to users for differential positioning of stationary points or mobile platforms, primarily in support of post-processing applications. Government, academic, and private users will be supported in performing after-the-fact positioning of fixed points and moving platforms by the infrastructure of the CORS.

## THE IGS AND CORS

### IGS Project for Regional GPS Densification

In December of 1994, an IGS workshop was conducted to develop plans for the consistent analysis of continuous GPS networks. This workshop, entitled "Densification of the International Terrestrial Reference Frame (ITRF) through Regional GPS Networks" (Zumberge and Liu, 1995) outlined an approach where the positions and velocities of essentially all continuous GPS stations can be determined accurately and precisely. This approach involves two different types of IGS Associate Analysis Centers (AAC): Regional Network Associate Analysis Center (RNAAC) and Global Network Associate Analysis Centers (GNAAC).

Regional Network Analysis Centers would analyze specific regional clusters of stations following IGS standards and flexible guidelines. For example, the cluster could be all or a subset of the CORS stations. The results of this analysis would be provided to the IGS.

Global Network Associate Analysis Centers would take the weekly GPS network solutions from all of the Analysis Centers, including the Regional Network analysis above, and produce combined network solutions. These Analysis Centers would conduct reference frame investigations, assess the quality of the solutions, and provide quality statistics. The findings would contribute to the annual update of the standard ITRF frame, and provide a highly reliable reference for the CORS network and other continuous regional arrays participating in the project.

This project model is also a good link between the IGS and CORS: it is the connection between the global reference frame and precise GPS orbits to the regional reference level for national consistency and high accuracy.

At this time, the IGS is involved in a pilot project to evaluate and establish these Analysis Centers. The IGS Analysis Center at JPL has proposed to be a Global Network Analysis Center, and further more, has been analyzing some of the CORS station data as the stations become available. JPL, as a GPS Analysis Center provides highly accurate information about the control, positioning and monitoring of the stations through daily analysis. Other Analysis Centers are also accessing and processing CORS station data, such as the IGS Analysis Centers at the NGS and Scripps Institution of Oceanography (SIO). A description of the techniques and approach of each Analysis Center is documented in the IGS 1994 Annual Report (Zumberge, et al., 1995).

## GPS ANALYSIS AT JPL

The Satellite Geodesy and Geodynamics Systems (SGGS) Group and the Earth orbiter Systems (EOS) Group-I at JPL are funded by the National Aeronautics and Space Administration (NASA) to participate as an Analysis Center (AC) for the international GPS Service for Geodynamics (IGS). Data has been analyzed from a globally-distributed network of continuous GPS receivers beginning with the first Global International GPS experiment in 1991 the GIG'91 Experiment. (Heflin, et al, 1992; Melbourne, et al, 1993).

The analysis strategy consists of using the ionosphere-free combination of both pseudorange and carrier phase, with data noise values of 1 cm and 1 m, respectively. Data below 15 degrees elevation are excluded. The phase data are decimated to 5 minute samples, and the pseudorange data are carrier-smoothed over the same interval.

Data corresponding to each GPS day are analyzed in 30-hour batches, centered on GPS noon. Estimated parameters were satellite state vectors and solar radiation pressure (srp), receiver coordinates, zenith wet troposphere delay at each receiver site, station and satellite clock offsets, carrier phase ambiguities, and Earth orientation. Satellite x- and y- srp and y-bias parameters are allowed to vary stochastically. Zenith wet troposphere delay is modeled as a random walk with 1 cm<sup>2</sup>/hr variance derivative, and is itself further analyzed for climatological applications.

Solid Earth and ocean tides are modeled largely in accordance with the IERS standards (McCarthy, 1992; Scherneck, 1991). The Earth's gravity field is described by the JGM-3 12x 12 multipole expansion using terms up through degree and order 12 (Watkins, et al, 1994). The value of GM used was 398600.4415 km<sup>3</sup>/s<sup>2</sup> (Ries, et al, 1992). Note that because of the use of the recent value of GM, the orbital ephemerides described below require a scale transformation in addition to rigid rotations to be expressed in the WGS-84 frame. Nominal values of the parameters for each GPS satellite (3 each for position and velocity, anti two for srp) are from the broadcast ephemeris. Weak *a priori* constraints of 1 km and 10 mm/s for position anti velocity, respectively, are imposed. The T10-T20 solar radiation pressure model is used for srp (Fliegel et al, 1992), while the new yaw attitude model (Bar-Sever, et al 1995) is applied for eclipsing spacecraft.

As an example, the analysis of January 21, 1994 included data from 43 stations and 25 satellites. There were nearly 60,000 phase and pseudorange measurements each, from which 1556 parameters were determined. (Parameters allowed to vary stochastically are counted only once. These include station and satellite clocks, station zenith wet troposphere delay, and satellite srp). The rms post-fit residuals for the phase measurements were typically a few mm. Those measurements with more than 5-cm post-fit residual for phase, or 5 m for pseudorange, were considered outliers and excluded.

## ANALYSIS PRODUCTS AND RESULTS

Recent results for station coordinates and Earth orientation, independent of errors in fiducial coordinates, are described in detail in the reference "Coordinates, Velocities, and EOP from the Jet Propulsion Laboratory Using GPS (Heflin et al, 1995). Contained in this same reference are contributions from other GPS Analysis Centers. Typical daily repeatabilities of site coordinates are 3, 5, and

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† Technical Groups within the Tracking Systems and Applications Section in the Telecommunications and Engineering Division of Caltech's Jet Propulsion Laboratory,

9 mm in the north, east, and vertical components, respectively, with respect to a global reference frame with origin at the Earth's mass center. Baselines between nearby sites can be significantly better due to cancellation of common orbit, clock, and media errors. The performance of the operational Earth orientation series with respect to the International Earth Rotation Service (IERS) Bulletin B Final values is below the 0.3-millisecond level, which is equivalent to less than 10 mm on the Earth's surface.

The single most important measure of orbit quality is the extent to which estimated values of a satellite's position near midnight agree with similar estimates based on data from adjacent days. For a given satellite and day we define the orbit repeatability  $Q$  to be the rms, during the 6 hours around midnight and over all 3 orbit position components, of the differences between the orbit computed using the current day's data and that computed with the previous (or next) day's data. Since there is only one "true" orbit during this period, the differences are a good measure of orbit accuracy. The value of  $Q$  is typically 10 - 20 cm (3-dimensional rms) during 1994-5. The precise orbits, and the GPS spacecraft clock offsets which are consistent with them, are routinely computed and made available to the public via computer networks. The nominal goal is to deliver a week's worth of products on Friday (or earlier) following the Saturday that marked the close of the previous GPS week.

### **PRECISE POINT POSITIONING: EFFICIENT PROCESSING OF LARGE NETWORKS**

In late 1994, in response to the growing number of continuously operating, regionally dense GPS sites (for example in California and Japan), JPL adopted a strategy of using an optimally selected global network of 34 sites to obtain accurate solutions for the GPS spacecraft orbits and clocks. The number 34 was selected as the minimum number which provide coverage as globally as possible with the current ground network, and this number will increase as more receivers are deployed in currently receiver-sparse geographic areas. The remaining sites (currently over 100, and including for example, a number of the CORS sites whose data are easily accessible) are analyzed with satellite parameters fixed at their just-determined values from the global solution. On a modern 40 Mflop workstation, these solutions take less than 2 cpu minutes per site for 24 hours of data.

The precise-point-positioning strategy has allowed that analysis of data from essentially all GPS sites that are accessible, with horizontal repeatabilities at the few-mm level, and vertical repeatabilities below the cm level. JPL supports that this strategy is the key to efficiently analyzing dense networks of hundreds of receivers, and furthermore that it is the appropriate method for most users, since millimeter-level coordinates are obtainable with no data other than that from the user's site. This is facilitated by using the highly reliable and accurate orbits and station positions made available through the IGS and its Analysis Centers.

To avoid the consequences of errors in fiducial coordinates, JPL has begun (April 2, 1995) to compute free-network orbits and clocks, and use these in every day's precise point positioning. Thus, coordinates of these sites will be in the same reference frame as those used in that day's free-network global solution. A free network solution is the analysis of the network data without implementing fiducial constraints or fixed coordinates until after the solution obtained.

Finally, in mid-1996 JPL plans to begin providing clock and orbit solutions at more frequent intervals (30 seconds or less as opposed to the current 5 minutes) to better serve kinematic users. High rate data from the CORS network, and at least from a subset of the stations, could be a potentially significant contributor to this effort.

## SUMMARY

The applications of the CORS system are wide-ranging and include land surveying, mapping, photogrammetric ground and aircraft control, geographic information systems (GIS), hydrographic surveys and mapping. CORS provides a reliable domestic infrastructure to support these numerous applications, just as the IGS provide the international framework for CORS and other national continuous networks worldwide.

## ACKNOWLEDGMENTS

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